Group coding of RF tags to verify the integrity of group of objects

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***Abstract*—RFID is an essential technology to uniquely identify physical objects. In many practical business processes using RFID, we check not only individual objects but also check if there is no missing objects and no extra objects in a group of objects. While individual objects identifications are done by using RFID, group verifications are usually done by looking up a shipping list or corresponding EDI data which require a network connection. In this paper, we propose "group coding of RF tags" by which we can verify the integrity of a group of objects just by writing additional data in RF tags' memory. The additional data is computed from unique IDs of objects that belong to the group. We propose fundamental and general group codings. With the fundamental group coding, we can check if the integrity of a group of objects is preserved or not. It is a parity check of hashes of unique IDs in a group. We also propose general group coding by extending the fundamental group coding. With the general group coding, we can estimate the number of missing objects if the integrity of a group is not verified. The strength of the missing number estimation can be controlled by the size of data written to RF tags. It can be considered as a Low Density Parity Check (LDPC) in physical objects. The theory of group coding is confirmed by a numerical simulation and an experiment. It is shown by the simulation and experiment that we can detect 10 missing RF tags out of 20 RF tags with 99.5% reliability by writing 96-bit data into each RF tags besides its 96-bit unique ID.**

I. Introduction

RFID, which is composed of RF tags, interrogator and associated information system, is an essential technology for "Internet of Things". With RFID, we can automatically and swiftly identify RF tagged object even when the object is non-line-of-sight from its interrogator. We also can write data into objects with RFID. These two aspects differentiate RFID from other automatic identification systems such as bar-code.

Any RFID, regardless of passive or active, basically identifies objects based on their unique identifiers (ID). It is a common practice in business that objects form a group and are handled together. When the integrity of a group of objects is required, for example at incoming shipment inspection, each object is identified first by RFID, then the integrity of the group is verified by looking up its shipment list or corresponding EDI (electric data exchange) data, typically ASN (Advanced Shipment Notification). This verification usually requires a network connection. EPCIS [1] defines events relating a group of objects as "aggregation event" and "quantity event" but how to establish such group of objects is out-of-scope of the standard. In certain circumstance, in addition, there is no network connection available, yet we need to verify the integrity of a group of objects. With this background observations, the authors are motivated to establish a method to verify the integrity of a group of objects without a network connection.

An exemplary usage scenario of group verification is as follows. Suppose a pallet carrying a group of RF tagged objects passes an RFID gate. We know there might be missing objects or read failure. If we can verify the integrity of the group, we just let the pallet go. If the integrity is not verified either by missing objects or a read failure, the system alerts and we restart the reading or check objects on the pallet with its shipping list or EDI data by looking up the on-line data base if we have a network connection. When we don't have a network connection, we need to check the group manually. The first screening with a group verification is a great help to reduce the labor. The estimated number of missing objects gives us a convenient indication on the degree of integrity loss.

This type of problem in RFID has been worked as yoking proof, grouping proof and co-existence proof ([2], [3], [4], [5], [6]). At the best of the authors' knowledge, Juels [2] first introduced the yoking proof of RF tags by chaining the message authentication code (MAC) with an external verifier. Other research essentially proposed to improve the security issue of the yoking proof. Lien [6] proposed a practical grouping method by obtaining an aggregated proof by adding sequence of proofs using XOR (exclusive OR operation). None of these researches has ever tried to record the grouping related data into RF tags to eliminate its external verifier. On the other hand, Inoue [7] proposed a method to detect missing object by a statistical analysis of reading data from various places. Potdar [8] proposed an interesting idea of using total weight of a group to check its integrity after transportation.

This paper proposes a method to verify the integrity of a group of objects just by writing and reading grouping related information into RF tags' memory. The propose method is referred to as group coding of RF tags. Authors see a similarity of group coding with FEC (Forward Error Correction) particularly packet level coding such as Tornado, LT and Raptor codes ([9], [10], [11], [12]) in an erasure communication channel. The objective of packet level coding, however, is fundamentally to reconstruct the sent data or stream at its receiver. It is, thus, presumed that we can reconstruct the graph of encoded packets at the receiver either by packet

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header information, time-synchronization or other application dependent means [12]. However, in group coding of RF tags, it is highly desirable to reconstruct the graph or its equivalent without any additional information because of the limitation in RF tag memory.

This paper is organized as follows. In Section II, fundamental group coding is introduced first. Then the false-positiveness of group coding is evaluated with a numerical analysis. Second, general group coding is introduced by extensively using the fundamental group coding. With the general group coding, we can verify the integrity of a group and estimate the number of missing objects. In Section III, the theory of group coding and fundamental performance are verified by a numerical simulation followed by an experiment using a commercial UHF RFID interrogator.

II. Theory of Group Coding

A. Fundamental group coding to check the integrity of a group

The fundamental group coding is composed of "group creation" and "group verification". Group creation involves the following steps:

1) Interrogator collects RF tag's unique IDs in a designated group.
2) The collected unique IDs are processed to yield their hashes by a group coding software. The hash process is important to handle a group of objects which contains sequential unique IDs.
3) Group coding software calculates bit-by-bit-XOR of all hashes, which results in a "group ID". The bit length of a group ID is the same as that of each hash.
4) Interrogator writes the group ID to user memory of each RF tags belonging to the group. In other words, all the RF tags in the group records its group ID in its user memory.

It should be noted that an object can belong to multiple groups by computing and writing multiple group IDs.

Group verification involves the following steps:

1) Interrogator reads unique IDs and the recorded group IDs in user memory of target RF tags.
2) Group coding software sorts the collected unique IDs in accordance with its group ID.
3) Group coding software calculates hashes of all unique IDs which belong to a group. The same hash function that is used in the group creation must be applied. Computed hashes are bit-by-bit-XORed to yield a calculated group ID.
4) Group verification software compares the calculated group ID and the recorded group ID. If there is no missing RF tag, these two group IDs must be the same. On the other hand, if the calculated group ID is different from the recorded group ID, there shall be some missing RF tags. Involvement of extra objects can be detected easily since extra objects usually do not have the same group ID of the target group because of the hash function. Our analysis reveals that 16-bit hash, generated by a linear feed back register, is sufficient for such purpose.

Overall procedure is shown in Fig.1.

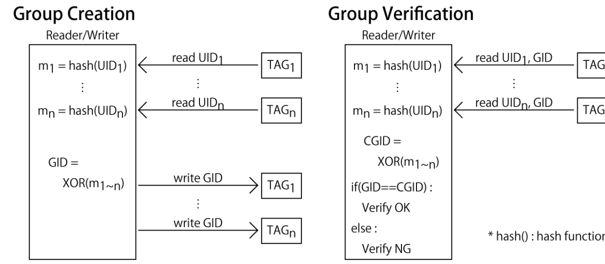

Fig. 1. Overall procedure of fundamental group coding

B. False-positiveness of fundamental group coding

There is a false-positive possibility where a group verification is valid although there are missing RF tags. Such false-positiveness occurs when the XOR of missing RF tags' hashes eventually is equal to zero. In this subsection, we analyze the probability of such false-positiveness.

When an RF tag in a group is missing, the group ID is invariant only if the hash of the missing RF tag, say m_j, is equal to 0. Suppose the bit length of hash (group ID) is L, the probability of the hash of one RF tag to be zero, P_1 is given by the following equation when we can presume uniformly distributed hash function.

$$P_1 = \frac{1}{2^L} \tag{1}$$

When two RF tags, j and k, in a group are missing, the group ID is invariant if

$$\boldsymbol{m_j \oplus m_k = 0}, \tag{2}$$

where "$\oplus$" represents bit-by-bit-XOR. The probability to hold Eq.2 is equivalent to the probability of

$$\boldsymbol{m_j = m_k}, \tag{3}$$

and thus the probability of sum of hashes of two RF-tag to be zero, P_2, is

$$P_2 = \frac{1}{2^L}. \tag{4}$$

Next, when 3 RF tags, j, k, and l, in a group are missing, the group ID is invariant only if

$$\boldsymbol{m_j \oplus m_k \oplus m_l = 0}, \tag{5}$$

which is equivalent to

$$\boldsymbol{m_j = m_k \oplus m_l}. \tag{6}$$

The probability P_3 is, thus, given by

$$P_3 = \frac{1}{2^L}. \tag{7}$$

The probability of invariant group ID subjected to arbitrary number of missing RF tags n is, therefore,

$$P_n = \frac{1}{2^L}. \tag{8}$$

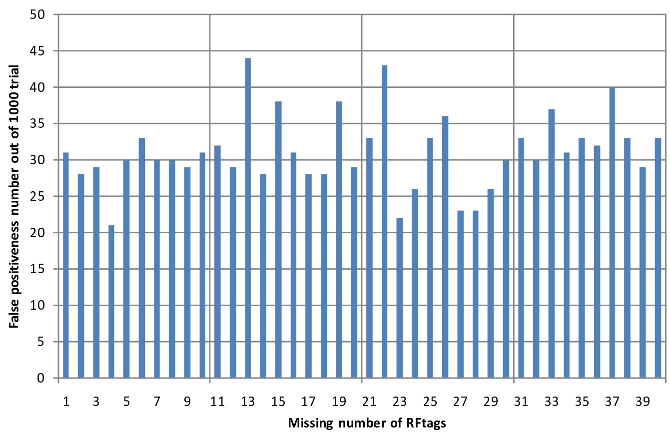

Fig. 2. Probability of missing RF tags yields false-positiveness of group ID

From Eq.8, it is obvious that false-positive probability becomes small enough with a sufficient bit length L. For example, with 16-bit group ID, false-positive probability is $\frac{1}{2^{16}}$ and can be ignored practically.

The above false-positiveness is verified with a numerical simulation. In the simulation, each RF tag is assigned a randomly generated 96-bit ID. We pick a designated number of RF tags and compute XOR of the hashes of the RF tags. We examined 1,000 trials for each number of picked RF tags (from 2 to 40). The hash of each unique ID is computed using CRC-5. We compute the bit-by-bit-XOR sum of the hashes for 1,000 trials to obtain the probability of false positiveness – the XOR sum is eventually equal to zero. Since the false positiveness in this case is $\frac{1}{2^L} = \frac{1}{32}$ because we use CRC-5, it is expected to have an average of 31.3 cases out of 1,000 trials. The computed result is shown in Fig.2. The average of the computed false-positiveness is 31.1 which agree well with the expectation.

C. General group coding

The fundamental group coding only uses one group ID to represent a group of RF tags. It can be considered an error detection using the group ID as L-bit parity. Strength of error detection can be controlled and the number of missing RF tags can be estimated by using mutually overlapping sub-groups, to which we apply fundamental group coding. This is the general group coding.

General group coding starts by reading all the RF tags' ID by using an interrogator. The general group coding software divides the target group, referred to as "main-group", into mutually overlapping sub-groups logically (Fig.3). General group coding software, then, generates sub-group ID according to the fundamental group coding in Subsection II-A. After the sub-group division, each RF tag records all the sub-group IDs that it belongs to in its user memory. This procedure is referred to as "group encoding".

If some RF tags are missing from the main-group, some sub-groups lose its integrity and the remaining sub-groups do not.

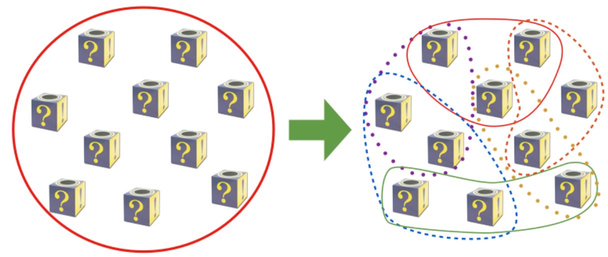

Fig. 3. The target group is divided into mutually overwrapping multiple sub-groups

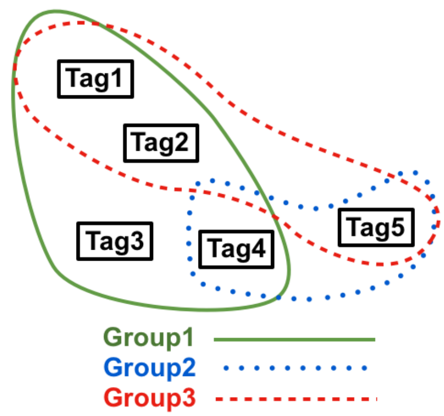

Fig. 4. Example of sub-group division

The system estimates the number of missing RF tags from the information of such incomplete sub-groups. This procedure is referred to as "group decoding" as the counterpart of "group encoding". In the followings, the details of group encoding and decoding are explained.

1) General group encoding: Suppose that a main-group has m RF tags and is divided into n sub-groups. An array of sub group IDs g_i in the main-group and its corresponding array of hashes of unique IDs m_i are correlated by the following equation.

$$\left\{ \begin{array}{c} g_1 \\ \vdots \\ g_n \end{array} \right\} = \left[\; G \; \right] \left\{ \begin{array}{c} m_1 \\ \vdots \\ m_m \end{array} \right\} \tag{9}$$

Matrix G yields a set of sub-group IDs from a set of hashes of unique IDs in the main-group. Since this is similar to the generation matrix in coding theory, this matrix G is referred to as "group generation matrix" in this paper.

For example, suppose that there are 5 RF tags and the number of sub-groups is 3. Sub-group 1 involves RF tags 1, 2, 3 and 4. Sub-group 2 involves RF tags 4 and 5. Sub-group 3 involves RF tags 1,2, and 5 as shown in Fig.4. An array of sub-group IDs can be derived by the following equations.

$$g_1 = m_1 \oplus m_2 \oplus m_3 \oplus m_4 \tag{10}$$
$$g_2 = m_4 \oplus m_5 \tag{11}$$

$$g_3 \quad = \quad m_1 \oplus m_2 \oplus m_5 \tag{12}$$

Note that g_i and m_i are L-bit vectors where L is the length of the hash. In this case, group generation matrix G has the following elements.

$$G = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

Generally, a group generation matrix should satisfy following conditions.

- Each row of a group generation matrix needs to be linearly independent. This is not to yield the same combinations of RF tags.
- The coding strength can be adjusted by changing the number of sub-groups and the number of RF tags in a sub-group to form a group generation matrix. Selection of RF tags for a sub-group needs to be done in a systematic manner. The number of sub-groups which one RF tag belongs to is particularly important because it has a direct relationship with the amount of data which is recorded in RF tag's user memory.

In this paper, the principle of LDPC (Low Density Parity Check) [13] is used to yield a group generation matrix G because its sparseness nature is effective to preserve independence among rows of a group generation matrix. Also the strength of coding can be controlled easily by increasing the number of sub-groups for an RF tag.

2) General group decoding: When some RF tags are missed from the main-group, Eq.9 can be partitioned into the following partial matrices

$$\left\{ \begin{array}{c} g_c \\ g_e \end{array} \right\} = \begin{bmatrix} G_{cr} & G_{cm} \\ G_{er} & G_{em} \end{bmatrix} \left\{ \begin{array}{c} m_r \\ m_m \end{array} \right\}, \tag{14}$$

where g_c and g_e represent the array of valid and invalid sub-group IDs, respectively. Please note both g_c and g_e are known because it is recorded in non-missing RF tags. m_r and m_m represent the arrays of non-missing (remaining) hashes and missing hashes, respectively. G_{cr}, G_{cm}, G_{er} and G_{em} represent corresponding partial matrices of group generation matrix. Among them, G_{cr} and G_{er} are known. G_{cm} can be considered as a zero matrix because the false-positive probability can be practically ignored as explained in Subsection II-B. Unknowns are, therefore, G_{em} and m_m because of missing RF tags. We can compute the product of these two unknowns: G_{em} and m_m, by using the reciprocal nature of XOR operation.

$$G_{em} m_m = g_e \oplus G_{er} m_r. \tag{15}$$

Since the rows of matrix $G_{em} m_m$ are linear combinations of missing hashes, the number of missing RF tags can be estimated as the rank of $G_{em} m_m$.

For instance, let us suppose there is a group of RF tags whose generation matrix is shown in Eq.13. When RF tags 2 and 4 are missing, all sub-groups lose their integrity and result in the following equation.

$$\left\{ \begin{array}{c} g_1 \\ g_2 \\ g_3 \end{array} \right\} = \left[\begin{array}{ccc|c} 1 & 1 & 0 & \\ 0 & 0 & 1 & G_{em} \\ 1 & 0 & 1 & \end{array} \right] \left\{ \begin{array}{c} m_1 \\ m_3 \\ m_5 \\ m_m \end{array} \right\} \tag{16}$$

The product $G_{em} m_m$ can be computed from known parameters as follows. Please note each row of the product $G_{em} m_m$ has L bit length.

$$G_{em} m_m = \left\{ \begin{array}{c} g_1 \oplus m_1 \oplus m_3 \\ g_2 \oplus m_5 \\ g_3 \oplus m_1 \oplus m_5 \end{array} \right\} = \left\{ \begin{array}{c} m_2 \oplus m_4 \\ m_4 \\ m_2 \end{array} \right\} \tag{17}$$

In this case, the rank of these elements are equal to the number of independent hashes, m_2 and m_4, and is two, accordingly.

TABLE I
CONDITIONS OF SIMULATION ABOUT ACCURACY OF ESTIMATION

Condition	Value
number of RF tags belonging to each sub-group	4
number of sub-groups which each RF tag belongs to	1-6 (variable j)
algorithm to calculate hash of RF tag's unique ID	CRC-16 (16-bit hash)

III. Evaluation of Group Coding

A. Numerical simulation on accuracy of missing number estimation

We evaluate the validity and the performance of the group coding by a numerical simulation in this subsection. The procedure of the simulation is outlined below.

1) We presume that the main-group is composed of 20 RF tags. Unique ID (96-bit EPC) of the RF tags are generated randomly.
2) We apply the group encoding to these RF tags. Conditions of the generation matrix is shown in Table I. As is shown in the Table, we change the number of sub-groups j that each RF tag belongs to. Large j indicates more overlapped sub-groups, which is expected to increase the reliability of the estimation of missing RF tags. We use CRC-16 to compute a hash from 96-bit EPC.
3) We eliminate n RF tags randomly from the main-group where n is between 1 and 19.
4) We apply the group decoding and estimate the number of missing RF tags.
5) For each combination of n and j, we apply randomly generated EPC and randomly chosen missing RF tags for 10,000 times and the error rate of estimation is calculated. Unless the group coding provides the exact number, the estimation is treated as an error.

The result of simulation is shown in Fig.5.

It is shown in the figure that the accuracy of the estimation increases with increasing the number of sub-groups which each RF tag belongs to. This result agrees with the theory that the strength of coding, accuracy of the estimation, can be controlled by increasing the number of sub-groups which each RF tag belongs to. For example, if 5 RF tags are missing, that

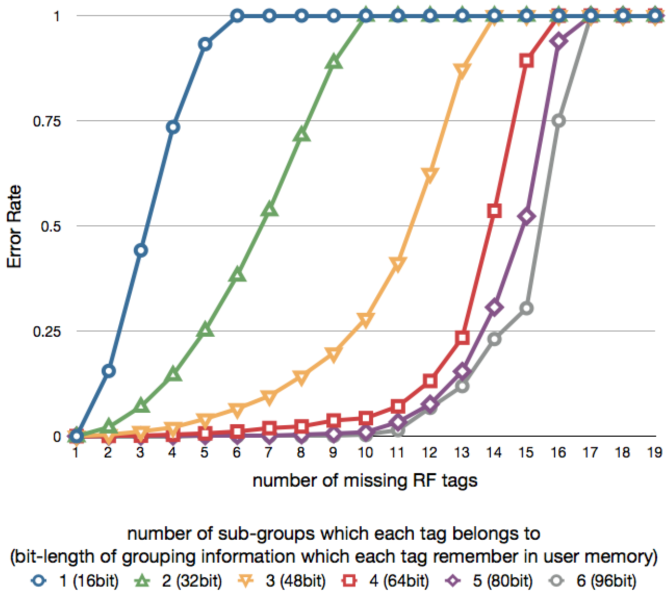

Fig. 5. Error rate of estimation

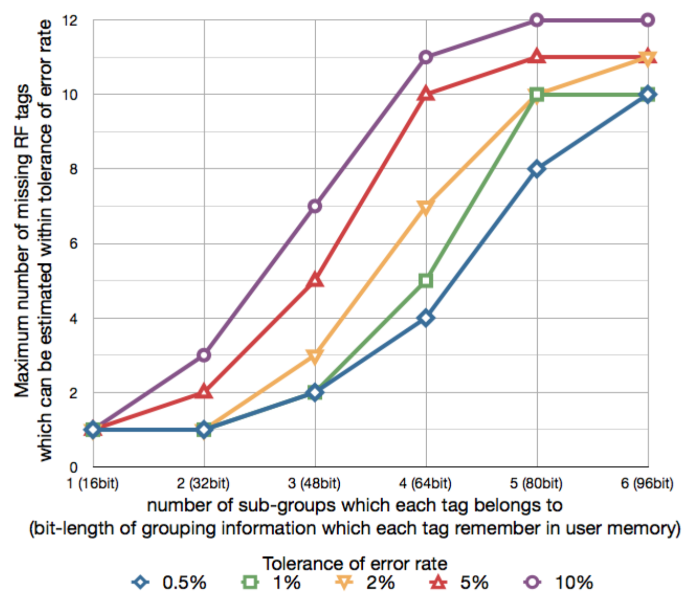

Fig. 6. Maximum number of missing RF tags which can be estimated within tolerance of error rate

number can be estimated accurately with at least 4 sub-groups to each RF tag: each RF tag has 64-bit additional information about grouping. On the other hand, if 10 RF tags are missing, 6 sub-groups: each RF tag has 96-bit additional information, are required to each tag for 99.5% reliable estimation (0.5% error rate). In other words, to estimate the same number of missing RF tags, the number of sub-groups can be reduced, if we can relax the reliability requirement.

The relationship between the number of sub-groups j which each RF tag belongs to and the maximum number of missing RF tags which can be estimated within the specified tolerance of error rate is shown in Fig.6. For example, 6 sub-groups: each RF tag has 96-bit additional information, are required to each tag to estimate the 10 missing RF tags within 0.5% error rate. On the other hand, if the tolerance of error rate is 5%, 4 sub-groups: 64-bit additional information, is enough.

B. Experimental evaluation using UHF RFID system

This section introduces the experimental evaluation of proposing group coding method on UHF-band RFID system. KU-U1601 RFID interrogator (Fig.7) provided by Panasonic System Networks Co., Ltd, which conforms to EPCglobal UHF C1G2 air protocol, is used in the experiment. The group encoding and group decoding computations are executed on a computer (PC) connected to the interrogator.

We examined the accuracy of group coding by comparing the result from the above simulation and experiment. The conditions of group coding are the same to TABLE I. The procedure of experiment is described below.

1) We have 20 physical RF tags. Unique ID (96-bit EPC) of these physical RF tags are generated randomly.
2) After group encoding, we eliminate N RF tags randomly and physically from the main-group. N is the maximum number of missing RF tags which can be estimated within a specified tolerance of error rate which is given by Fig.6. For example, if j is 6 and the tolerance of error rate is 0.5%, 10 RF tags are removed from the group.
3) We examined this procedure for 0.5% and 10% tolerance of error rate and estimated the number of missing RF tags with group decoding procedure.
4) Repeat the above procedure 10 times for each j, then calculate the average of results of the estimation.

Fig. 7. Panasonic KU-U1601 RFID interrogator

The result of experiment subjected to 0.5% error rate with the simulation result as a reference is shown in Fig.8. The experimental results completely agree with the simulation. The group coding provides the exact number of missing RF tags ten times out of ten trials. The result of experiment subjected to 10% error rate is shown in Fig.9. There are little differences between the experiment and the simulation in this case where the number of sub-groups is 2 and 3. One out of ten trials provided a wrong estimation of missing RF tag number.

These figures show that both of the result of experiment

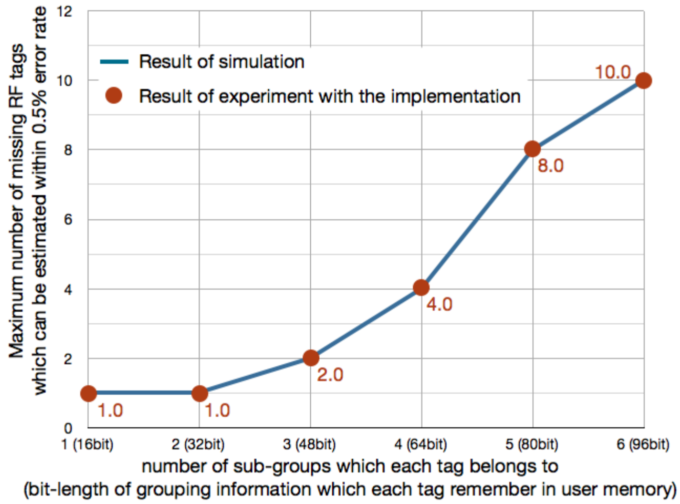

Fig. 8. Comparison between the result of simulation and experiment (0.5% error rate)

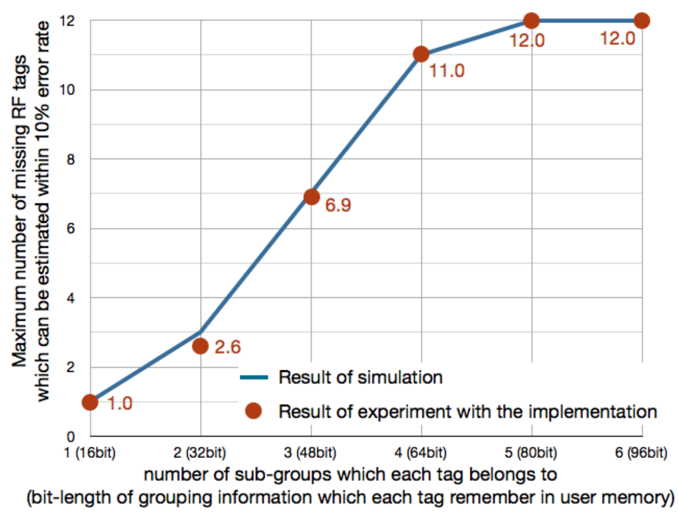

Fig. 9. Comparison between the result of simulation and experiment (10% error rate)

agree to the expectation and prove the group coding works.

We also evaluated the time consumed to execute a group encoding and decoding which include the time to access RF tags wirelessly. To measure the time, a Battery Assisted Passive tag (BAP, Fig.10 [14]), was used to capture air command emitted from the interrogator. The BAP listens to the interrogator air protocol and measure the timing of inventory, user data reading and writing. The measured data is sent from the BAP to a computer via RS-232C interface, and a computer establishes a time line of commands from the collected data. Fig.11 shows the experimental set up.

The result of time measurement of group encoding and decoding are shown in TABLEs II and III, respectively. From this result, it is clear that the calculation of group coding can be done in a very short time. On the other hand, 80

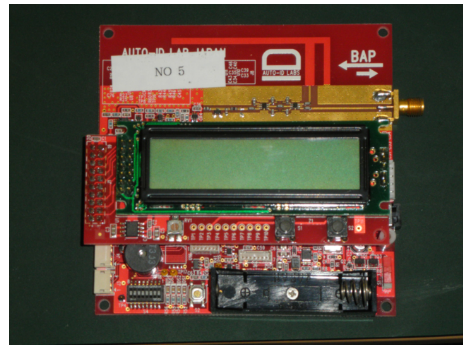

Fig. 10. BAP: Battery Assisted Passive tag

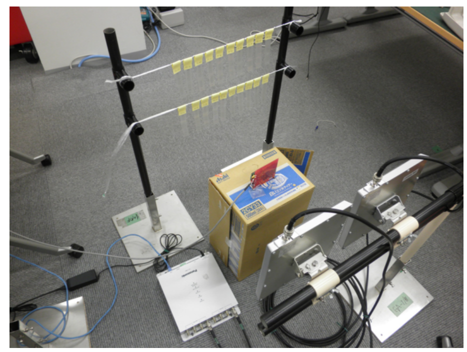

Fig. 11. The environment of measurement

TABLE II
GROUP ENCODING TIME DURATION STRUCTURE

Process	Time
RF tag inventory	about 2 seconds
Calculation of group encoding	about 2 milliseconds
Writing group IDs to 20 RF tags' user memory	more than 80 seconds

TABLE III
GROUP DECODING TIME DURATION STRUCTURE

Process	Time
RF tag inventory	about 2 seconds
Reading group IDs from 20 RF tags' user memory	about 80 seconds
Calculation of group decoding	about 1 millisecond

seconds for reading and writing is too long and not suitable for practical use. With the time line generated by the collection of air protocol, it was found that this long reading and writing time are caused by the following mechanism. Read and Write function in the API, which is called to read from and write to RF tag's user memory, do not keep the handle of RF tag between multiple function calls. In other words, the execution of these functions must start with "Select" command every time in air protocol. The API calls these functions repeatedly to access each RF tag at the same time, so many redundant "Select" commands are executed. This problem can be improved by optimizing the access to RF tags.

IV. Conclusion

This paper proposes “Group coding”, which verifies the integrity of groups of multiple RF tags even when there is no network connection. Group coding can be done by writing grouping related data into RF tag’s user memory. We developed the fundamental group coding and the general group coding. The fundamental group coding can verify if the integrity of a group is preserved or not. By extensively using fundamental group coding for overlapped sub-groups, the general group coding can estimate the number of RF tags missing from the group if the integrity of the group is not verified. The error detection accuracy of the general group coding can be controlled by adjusting the amount of data recorded in an RF tag. General group coding can be considered to be an LDPC in physical objects. Strong group coding can be achieved with an expense of user memory. We implemented the group coding on UHF RFID system and evaluated the performance and proved that the group coding can work as expected in physical system. It is revealed both by a numerical simulation and an experiment that we can predict the number of missing RF tag up to 10 out of 20 RF tags with 99.5% reliability by writing 96-bit data into RF tags. The memory consumption can be relaxed to 64-bit when we can reduce the reliability to 95.0%.

Acknowledgements

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